Impact of High Photo-Voltaic Penetration on Distribution Systems

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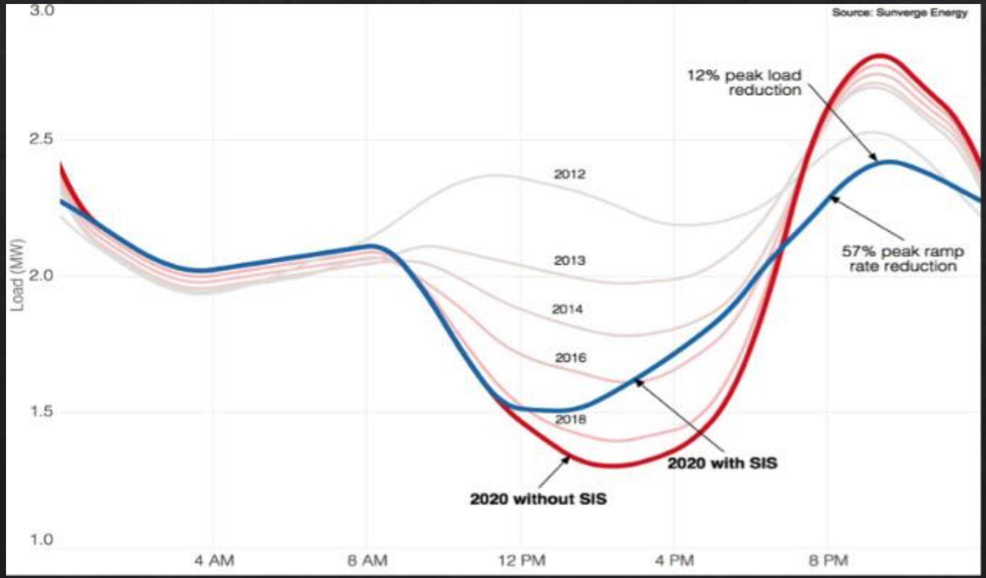
Project Plan

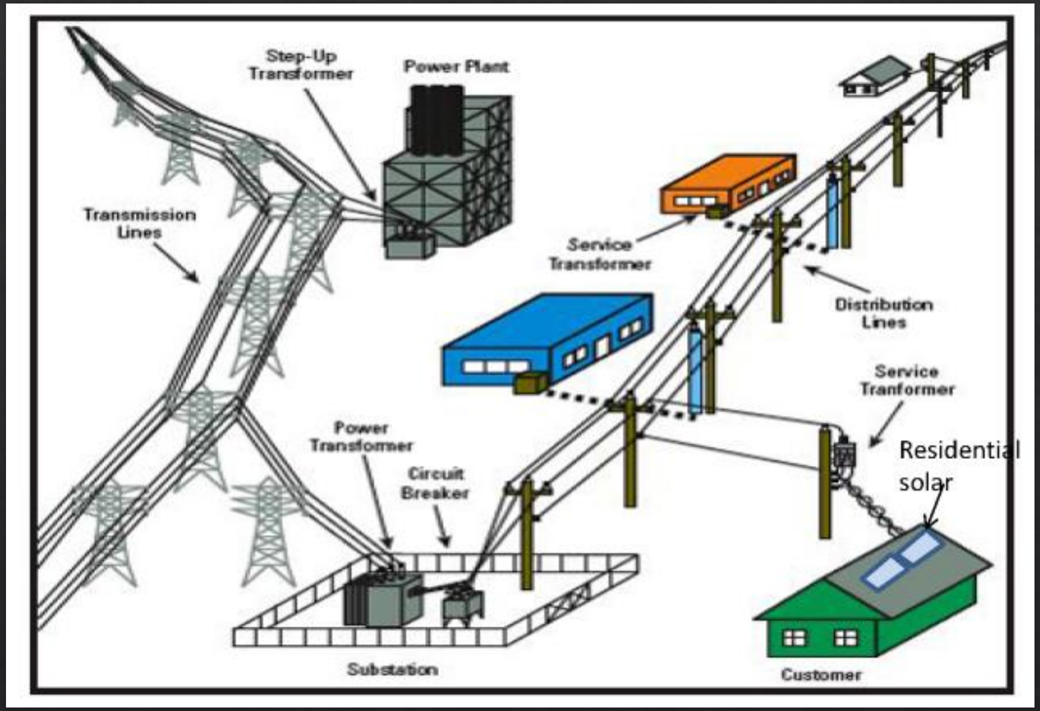
High level Overview

- Environmental and economic incentives for solar development
- Advancements in solar technology – some research cells at ~50% efficiency [1]
- Two methods of solar integration – Community and Rooftop
  - Community: Central location with many solar cells
    - Offers more direct utility control
  - Rooftop model : Many consumers have their own private solar cells
    - Common in less regulated green communities
    - May cause issues with reverse power flow
- Importance of voltage regulation : Maintain voltage profile
  - Direct voltage regulation through inverters or regulators
  - Power injection – for example, solar!



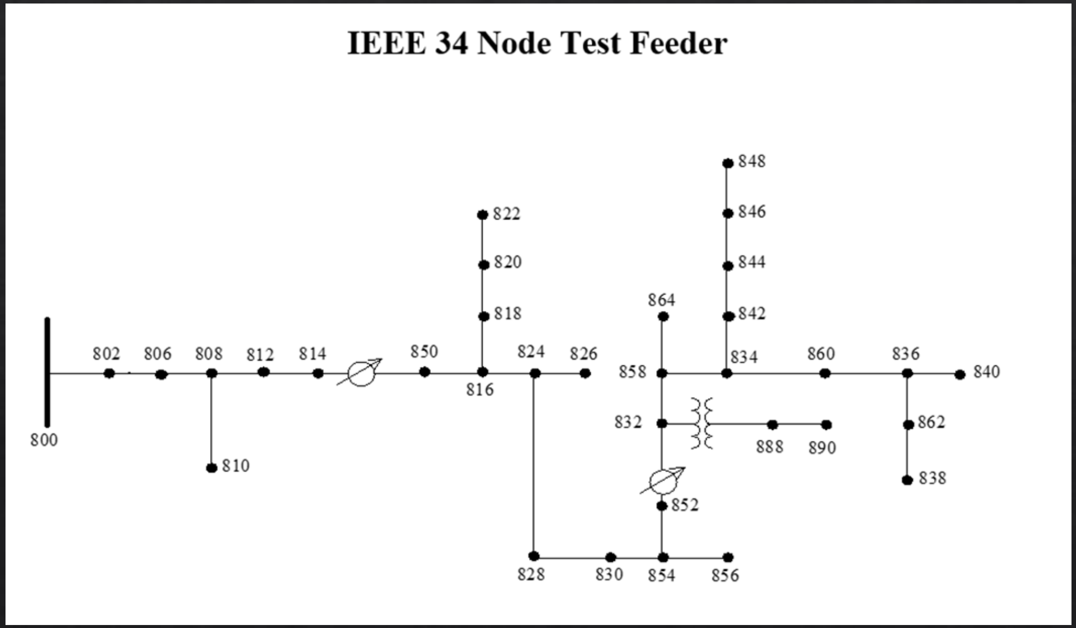
Problem Statement

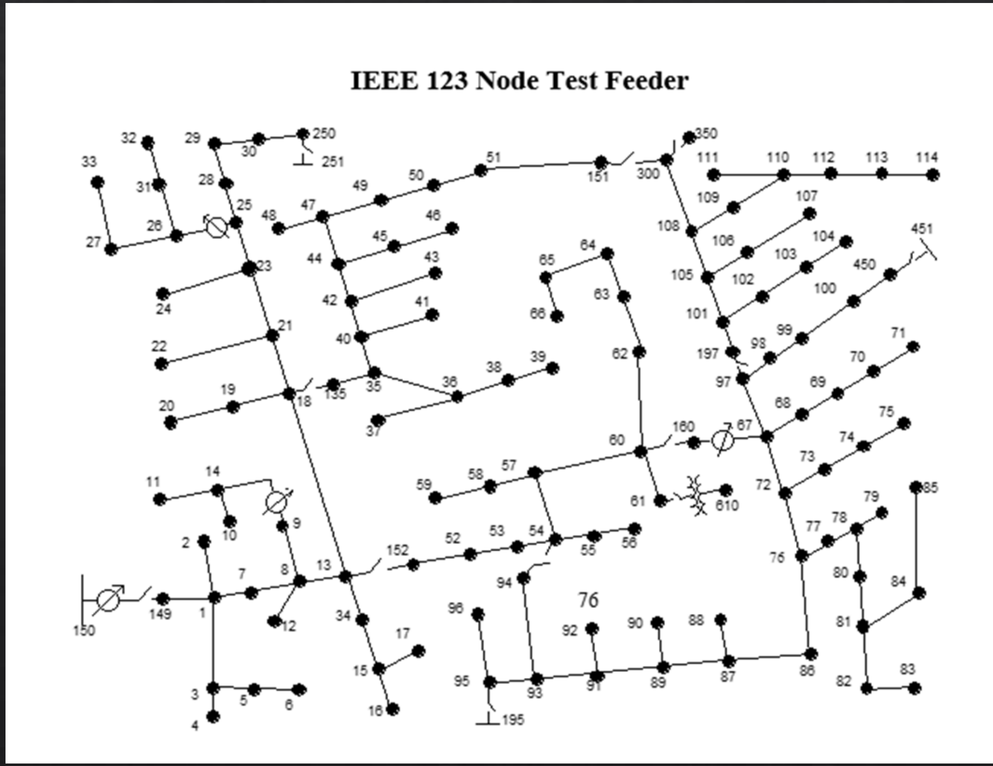
- Solar Power inverters and their use for KVAR Injection
  - Model distribution feeder network and distributed solar cells
  - How much penetration is necessary to regulate voltage acceptably?
- Optimizing power flow losses – community or distributed?
  - Both methods of PV implementation can be used for minimizing power losses in distribution systems. The issue of distributed solar is the utility has no control over the size and location due to being installed on consumer homes. Because community solar can be sized and set, it is analyzed for optimization.



IEEE Distribution Feeder One Line Diagrams

- Both systems are examples of radial distribution feeders.





Functional Requirements

- Ensure addition of PV does not increase losses or degrade voltage profile.
- Design optimization and voltage regulation procedures that are extensible to other systems.
- Maintain voltage between 0.95-1.05 p.u. and currents within line ratings.
- No real power injection from the distribution system to the transmission system through the substation transformer.

Engineering Standards & Design Practices

- The addition of distributed and spot PV generation to distribution systems causes changes in voltage profile and power flow. Voltages must be maintained between 0.95 and 1.05 per unit, currents in distribution lines must not exceed rated ampacity of the line, and KVA ratings of the transformers shall not be violated during operation of the system.
- IEEE Std 1547™-2018 requires that at least 44% of inverter capacity be reserved for KVAR injection if needed by the utility.

Technical/other constraints/considerations

- Limitations of OpenDSS daily solve mode
  - A solution set consists of 100 power flow solutions with differing levels of PV implemented. Each power flow solution is 48 iterations of the system model, representing a 24 hour day in 30 minute intervals. Dynamic inverter control would ideally use one 30 minute solution to define the operation of the inverter in the next 30 minute period. This level of detail is not possible using the daily solve mode, and as such static inverter operation modes were implemented. It is possible that dynamic control would allow for implementation of voltage control at lower %PV penetration than we determined using static operation.
- Program operation time constrains
  - The larger solution sets used for the 123 Node system, particularly the 100x100 solution set matrix, requires an extremely long time to run, largely owing to the large number of file operations associated with altering the OpenDSS model. If the number of file operations needed for a given system could be reduced, runtime would improve. For the systems we used, power flow solve time was not a significant factor.

Potential Risk & Mitigation

- Due to the effects of the COVID-19 pandemic, team and advisor meetings are held remotely where possible, and MATLAB and OpenDSS scripts have been updated to allow them to run on personal computers rather than senior design lab computers.
- Otherwise, there are no foreseeable health or safety risks due to the simulation-based nature of our project.

Cost and Resources Required

- No cost associated with project
- Programs Required
  - MATLAB – Free student license provided through the university
  - OpenDSS – Free open source software
- Processing power required for iterative calculations
  - 123 Node [AxB] solution matrix (% Penetration and % Inverter capacity)
    - 100x100 : 7 Hours on an Intel(R) Core(TM) i7-8700 CPU @ 3.20ghz
    - 1x100 : 5.388 Minutes on an Intel(R) Core(TM) i7-8700 CPU @ 3.20ghz

System Design

Detailed Design

- 34 Node Optimization
  - The 34 Node system will be analyzed to determine the sizing and setting of up to two community solar plants for the purpose of minimizing losses. Each node connected to a 3-phase line will be considered for solar placement. A secondary solar site will be considered based on the lowest voltage node for possible improvement on power loss reduction.
- 123 Node Voltage Regulation
  - Solar inverters will be operated in constant KVAR mode. Every combination of %KVAR injection and %PV penetration will be tested to determine the minimum % PV required for voltage control. A specific %KVAR injection corresponding to a limit imposed by a hypothetical utility company will be tested to develop a specific recommendation for improving voltage profile, with a secondary objective of minimizing MWh losses.

HW/SW/Technology Platforms used

- MATLAB
  - Data Input
    - Simple interface with .csv files
    - Easy to adjust between 34/123 node
    - Optimization
  - COM Interface
    - Controller script used to run OpenDSS files and output data
- OpenDSS – power system simulation
  - Easy to learn code suite
  - Decent runtime

Test plan

34-Node Optimization with Constant Power Factor

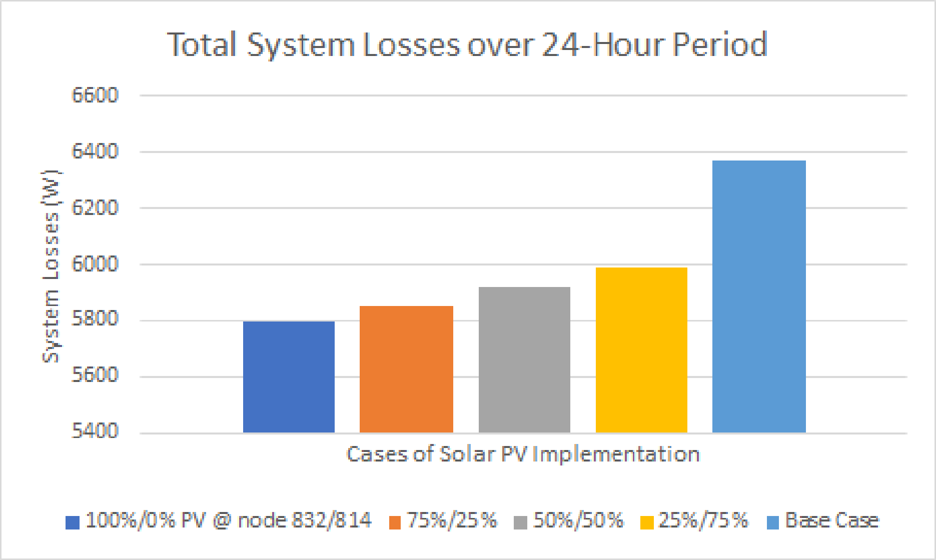
- Run to simulation with no PV to get a base case for the system.
- Determine the max size of PV that can be implemented at each node using data from the base case.
- Implement PV at each node. The node that produces the least amount of power loss throughout the system is the primary injection site and the size is the max amount of PV that will be added.
- Using the voltage profiles generated from the base case we determined which node had the most out of spec voltage. This node became our secondary injection site.
- Iterate from 1-100% and split the PV that is added to the system between the primary and secondary injection site to determine how much should be placed at each location.

123-Node test feeder

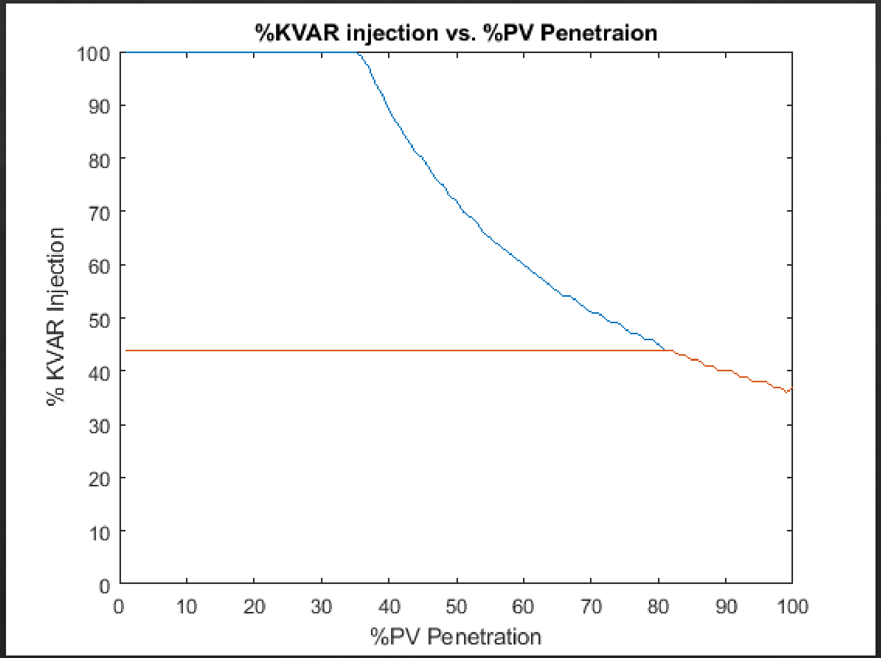
- Iterate from 1-100% for both KVAR injection and %PV penetration to develop a minimum KVAR injection curve for all levels of PV penetration.
- Based on the resulting curve, determine what % PV penetration is required for voltage control for a given %KVAR rating reserved by the utility. For our purposes, 44% was used as a realistic example value, corresponding to a power factor of 0.915.
- Re-run the simulation for the example %KVAR injection to determine which mode of operation will minimize losses at %PV penetration less than the benchmark for complete voltage control.
- Develop a recommendation for solar inverter operation based on loss minimization until %PV penetration reaches the threshold for voltage control, as which point inverters should be operated on the curve generated from step 1.

Results

34-Node



123-Node



Project Milestones

- Textbook reading to understand distribution systems – September 2019
- Hand calculations for 4-node example – September 2019
- MATLAB 4-node example – September 2019
- OpenDSS 4-node example – November 2019
- 34-node example OpenDSS initial solution – November 2019
- Observe 34-node example over a 24-hour load period – November 2019
- Add photo-voltaic penetration to 34-node – December 2019
- Observe 123-node system over a 24-hour load period – February 2020
- Model IEEE 123-node Test Feeder (Data input, loadshape, analysis) – April 2020
- Optimize 34-node community PV implementation – April 2020

Schedule : Fall Gantt Chart

Schedule : Spring Gantt Chart

Task Name	1/13-1/19	1/20-1/26	1/27-2/2	2/3-2/9	2/10-2/16	2/17-2/23	2/24-3/1	3/2-3/8	3/9-3/15	3/16-3/22	3/23-3/29	3/30-4/5	4/6-4/12	4/13-4/19	4/20-4/26	4/27-5/3
	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16
34 Node Example																
Write code in MATLAB for running OpenDSS inside script																
Write program in MATLAB for incremental addition of PV (spot and distributed)																
Incrementally add PV using program and gather data																
Analyze data to determine how PV affects the network																
123 Node System - Chaney, Prell																
Adjust data input MATLAB scripts																
Troubleshoot controller script																
Test different PV levels																
Analyze results of PV injection types																
Prepare recommendation																
34 Node Optimization (Spot PV) - Riley, Coleman										Spring Break						Finals Week
Write Powerflow in MATLAB																
Use guidelines of multi-PV setting for determining PV locations																
Analyze system losses based on multi-PV setup																
Choose best location of spot PV for most loss reduction																
Prepare recommendation																
Final Writeup of Design Document/Poster/Presentation																
Prepare poster																
Revise design document to reflect progress for end of term																
Finalize presentation in preparation for industry review																

Conclusion

- In the second semester of our project, our work diverged into two subprojects. One was focused on simulating and analyzing another IEEE test feeder case, the 123-Node system. We were able to successfully adjust the system to run as desired and found that voltage control via only PV inverter control was possible. A specific level of KVAR injection (44% of inverter capacity reserved) for a hypothetical utility company was examined to determine the system losses as %PV penetration increased. Based on these 2 conclusions, the recommendation was made to operate in 44% KVAR injection below 81% PV, and following the generated curve above 81%.
- The other subproject was 34-Node optimization, with the goal of reducing power losses. This subproject had the result of determining that the optimal type was community PV and the optimal place to inject PV was at node 832 with 316kw of PV being injected at that site. Furthermore, we also concluded that the type of control used, constant power factor, was not sufficient for this system since the voltage at node 814, the secondary injection site, did not improve as the PV injection was split between nodes 832 and 814 and power losses increased as capacity was moved from node 832 to node 814.
- In our efforts in this project, we have completed power analysis of several distribution systems and reviewed the impact of solar energy penetration. While we were not able to analyze real life systems as was originally planned, our work will serve as a springboard for future groups working in this area. To this end, we have annotated our code and provided instruction to future users.

Future Prospects

- Since this is a project that is repeated for further study, any future groups can use our data and resources to not only approach this project from a different angle, such as a different method of optimization, and they could get through the beginning stages of the project quicker than we were able to.
- Senior Design projects under Dr. Ajjarapu are planned to use our work as a starting block
  - Data Input Scripts can easily be altered
  - New groups could study our work to build knowledge on distribution system operation
- Future projects
  - Analysis of larger systems (1000+ nodes) – would require serious processing power or code optimization (reduction in read/write operations)
  - More fine-tuned optimization – find which exact node best reduces power losses

Member Responsibilities

Andrew Chaney

- 34 Node: System model development, loadshape and solar PV integration, data acquisition and manipulation, development of functions needed for optimization.
- 123 Node: Data input scripting, modification of MATLAB and OpenDSS scripts to be extensible to 123 Node system, 123 Node simulation and analysis, recommendation development.
- Admin: Design Document/Final Report, GitHub Organization and Maintenance.

Thomas Coleman

- Optimization 34-Node: Power-flow script, data retrieval script, finding optimal node(s) for community solar for maximum loss reduction
- Admin: Weekly/Biweekly reports, Final Report, Uploading and editing documents in website

Kenneth Prell

- 4 Node : Math By Hand, OpenDSS
- 34 Node : Data Input Scripts, Implementation of PD elements, Analysis
- 123 Node : Data Input Scripts, Implementation of PD elements, Analysis
- Admin : Weekly Reports, Design Document / Final Report, GitHub Organization

Daniel Riley

- 4 Node: Math by Hand, OpenDSS
- Optimization 34-Node: IMO calculation script, PV Sizing script, Analysis
- Admin: Weekly Reports, Bi-weekly Reports, Final Report, Poster Design, Presentations

Citations

[1] Kenneth Munson, Integrated Energy Storage: An Answer to Addressing the Duck Curve? https://www.renewableenergyworld.com/2015/04/08/integrated-energy-storage-an-answer-to-addressing-the-duck-curve/

[2] K. Seepromting, R. Chatthaworn, P. Khunkitti, A. Kruesubthaworn, A. Siritaratiwat and C. Surawanitkun, "Optimal Grid-Connected with Multi-Solar PV Placement and Sizing for Power Loss Reduction and Voltage Profile Improvement," *2018 18th International Symposium on Communications and Information Technologies (ISCIT)*, Bangkok, 2018, pp. 479-483.

[3] D. Q. Hung, N. Mithulananthan and K. Y. Lee, "Determining PV Penetration for Distribution Systems With Time-Varying Load Models," in *IEEE Transactions on Power Systems*, vol. 29, no. 6, pp. 3048-3057, Nov. 2014.